Entangling two atoms in spatially separated cavities through both photon emission and absorption processes

Peng Peng and Fu-li Li*

Department of Applied Physics, Xi'an Jiaotong University, Xi'an 710049, China

(Dated: January 1, 2007)

Abstract

We consider a system consisting of a Λ-type atom and a V-type atom, which are individually trapped in two spatially separated cavities that are connected by an optical fibre. We show that an extremely entangled state of the two atoms can be deterministically generated through both photon emission of the Λ-type atom and photon absorption of the V-type atom in an ideal situation. The influence of various decoherence processes such as spontaneous emission and photon loss on the fidelity of the entangled state is also investigated. We find that the effect of photon leakage out of the fibre on the fidelity can be greatly diminished in some special cases. As regards the effect of spontaneous emission and photon loss from the cavities, we find that the present scheme with a fidelity higher than 0.98 may be realized under current experiment conditions.

PACS numbers: 03.67.Mn, 03.65.Ud, 42.50.Pq, 42.81.Qb

*Email: flli@mail.xjtu.edu.cn

I. INTRODUCTION

Entangled quantum state is one of essential key ingredients in the implementation of quantum communication and quantum computation [1, 2, 3, 4]. Among kinds of schemes proposed to generate entangled states [5, 6, 7, 8, 9], cavity quantum electrodynamic systems(CQEDS), which marry atomic and photonic quantum bits together, are paid more attentions because of both its low decoherent rate and promising feasibility to scale-up. In recent years, several elegant works based on CQEDS have been done. In [10], a pair of momentum- and polarization- entangled photons is sent to two spatially separated cavities, each of which contains a V-type atom. After the atoms absorb the photons, the photon entanglement is transferred to the atoms. In [11, 12, 13, 14], entangled states of two Λ-type atoms individually trapped in spatially separated cavities are generated through the interference of the polarized photons leaking out of the cavities on a beam splitter and co-instantaneous single-photon detections. In these schemes, in order to guarantee the interference effect, several conditions are required. First, the two atoms have to be simultaneously excited or driven. Second, spatial shapes of photon pulses leaking from the cavities should be similar. Third, the two photon paths from the cavities to the beam splitter must be symmetrical. In addition, the success of generating entangled atomic states is probabilistic since the photon-state-projection detection behind the beam splitter is performed. We also notice that the previous schemes are based on either photon emission or photon absorption process. In this paper, we consider a CQED system in which a Λ-type atom and a V-type atom are trapped individually in two spatially separated cavities that are connected by an optical fiber. This setup is closely related to two previous schemes. In [15], Pellizzari proposed a cavity-fibre-cavity system to realize reliable transfer of a quantum state. In that scheme, two three-level Λ atoms that are adiabatically and simultaneously driven by a laser beam are trapped individually in two single-mode cavities connected via an optical fibre. In [16], Serafini et al employed the similar setup in which two-level atoms are trapped in fibre-connected cavities to realize highly reliable swap and entangling gates. We notice that quantum information processes realized in the fibre-connected cavity setup depends on atomic level configurations and laser driving ways. In the present scheme, without using any laser driving, only the Λ-type atom is initially to be pumped in the excited state. Instead of using either photon absorption or photon emission as done in the previous scheme, both the photon emission of the Λ-type atom and the photon absorption of the V-type atom are involved. In this way, an entangled state of the two atoms can deterministically be generated through the atom-field interaction without the photon interference and the photon-state projection detection.

II. MODEL

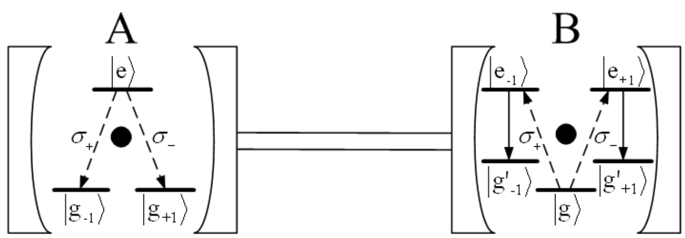


FIG. 1: A Λ type atom and a V-type atom are trapped in two spatially separated cavities A and B, respectively. The two cavities are linked through an optical fibre.

As shown in Fig.1, a Λ-type atom with two degenerate states $|g_{-1}\rangle$ and $|g_{+1}\rangle$ and a V-type atom with two degenerate states $|e_{-1}\rangle$ and $|e_{+1}\rangle$ are trapped in two spatially separated cavities that are linked by an optical fibre. The two atoms interact with local cavity fields, respectively. In recent years, such fiber-connected cavity systems are often empolyed for realizing quantum information processes [15, 16, 17].

The Hamiltonian of the whole system can be written as [15]

$$H = H_A + H_B + H_F, \tag{1}$$

where

$$H_A = \sum_{j=\pm 1} \Big[\omega^f_{A,j} a^+_{A,j} a_{A,j} + \omega^a_A \sigma^z_{A,j} + \lambda_{A,j} a_{A,j} \sigma^+_{A,j} + \text{H.c.}\Big], \tag{2}$$

$$H_B = \sum_{j=\pm 1} \Big[\omega^f_{B,j} a^+_{B,j} a_{B,j} + \omega^a_B \sigma^z_{B,j} + \lambda_{B,j} a_{B,j} \sigma^+_{B,j} + \text{H.c.}\Big], \tag{3}$$

$$H_F = \sum_{k=1}^{\infty} \sum_{j=\pm 1} \Big[\omega_{j,k} b^+_{j,k} b_{j,k} + \nu_{j,k} b_{j,k} [a^+_{A,j} + (-1)^k e^{i\phi} a^+_{B,j}] + \text{H.c.}\Big], \tag{4}$$

where $H_{A/B}$ is the energy of the system consisting of atom A/B and the corresponding local cavity fields, and H_F represents the free energy of fibre modes and the interaction between cavity and fibre modes. In (2)-(4), $a_{A/B,j}$ and $a^+_{A/B,j}$ are annihilation and creation operators for photons of frequency $\omega^f_{A/B,j}$ and polarization j(= -1,+1 corresponding to right and left circular polarizations, respectively) in cavity A/B, and $b_{j,k}$, $b^+_{j,k}$ are annihilation and creation operators for photons of frequency $\omega_{j,k}$ and polarization j in mode k of the fibre field, $\sigma^z_{A,j} = (|e\rangle\langle e| - |g_j\rangle\langle g_j|)_A/2, \sigma^z_{B,j} = (|e_j\rangle\langle e_j| - |g\rangle\langle g|)_B/2$, $\sigma^+_{A,j} = (|e\rangle\langle g_j|)_A$ and $\sigma^+_{B,j} = (|e_j\rangle\langle g|)_B$, $\omega^a_{A/B}$ is the frequency of the transition $|e/e_j\rangle \to |g_j/g\rangle$, $\lambda_{A/B,j}$ is the coupling constant of atom A/B with cavity mode j, and $\nu_{j,k}$ the coupling constant of cavity mode j with fibre mode k. Here, we assume that the right and left circular polarization modes in both the cavities have the same frequency ω and the interaction between the atoms and the cavity fields is on resonance. That is, $\omega^f_{A,\pm1} = \omega^f_{B,\pm1} = \omega^a_A = \omega^a_B = \omega$.

In the short fibre limit $(2L\bar{\nu})/(2\pi C) \leq 1$, where L is the length of fibre and $\bar{\nu}$ is the decay rate of the cavity fields into a continuum of fibre modes, only resonant modes b of the fibre interacts with the cavity modes [16]. For this case, the Hamiltonian H_F may be approximated to

$$H_F = \sum_{j=\pm1} \big[\omega b^+_j b_j + \nu_j b_j (a^+_{A,j} + a^+_{B,j}) + \text{H.c.}\big], \tag{5}$$

where the phase $(-1)^k e^{i\phi}$ in (4) has been absorbed into the annihilation and creation operators of the modes of the second cavity field.

In the interaction picture, the total Hamiltonian now becomes

$$H_I = \sum_{j=\pm1} \big[\lambda_{A,j} a_{A,j} \sigma^+_{A,j} + \lambda_{B,j} a_{B,j} \sigma^+_{B,j} + \nu_j b_j (a^+_{A,j} + a^+_{B,j}) + \text{H.c.}\big]. \tag{6}$$

III. THE GENERATION OF ENTANGLED STATES

In this section, we show that an extremely entangled states of the atoms can be deterministically generated in an ideal situation.

To explain the scheme of the generation of entangled states, first, let us see how the entangling process works. Suppose that at the initial time the atom A is pumped in the excited state $|e\rangle_A$ and the atom B is in the ground state $|g\rangle_B$. Through interacting with local cavity fields, the atom A emits either a σ_+ or σ_- polarized photon and then the atom-field system is in the state $|\Psi_1\rangle = \frac{1}{2}(|g_{-1}\rangle|1_{\sigma_+}\rangle + |g_{+1}\rangle|1_{\sigma_-}\rangle)$, where $|1_{\sigma_+}\rangle/|1_{\sigma_-}\rangle$ is a cavity field state with one photon in mode $j = -1/+1$. Assume that the coupling of the cavity modes with fibre modes is so strong that the emitted photon can be transferred into the fibre modes before reabsorbed by the atom A. Through the fibre, the photon enters the cavity B. After absorbing the photon, the atom B is excited in either $|e_{-1}\rangle_B$ or $|e_{+1}\rangle_B$. In this way, the entangled state $|\Psi_t\rangle = \frac{1}{\sqrt{2}}(|g_{-1}\rangle_A|e_{-1}\rangle_B + |g_{+1}\rangle_A|e_{+1}\rangle_B)$ can be created. In order to protect the entangled state from spontaneous emission, as shown in Fig.1, one may apply a π-polarized light to the transition between $|e_{\pm1}\rangle_B$ and $|g'_{\pm1}\rangle_B$, and generate a stable entangled state: $|\psi_s\rangle = \frac{1}{\sqrt{2}}(|g_{-1}\rangle_A|g'_{-1}\rangle_B + |g_{+1}\rangle_A|g'_{+1}\rangle_B)$, where $|g_{\pm1}\rangle_A$ and $|g'_{\pm1}\rangle_B$ are stable states.

Now, let us go to investigate the generation of the entangled state in detail. The time evolution of the whole system state is governed by the Schrödinger equation

$$i\frac{\partial}{\partial \mathrm{t}}|\psi_1(t)\rangle = H_I|\psi_1(t)\rangle. \tag{7}$$

Suppose that at the initial time the system is in the state $|\psi_1(0)\rangle = |e\rangle_A|0\rangle_A|0\rangle_f|0\rangle_B|g\rangle_B$. The state vector $|\psi_1(t)\rangle$ at time t can be expanded as

$$\begin{aligned}|\psi_1(t)\rangle &= d_1|e\rangle_A|0\rangle_A|0\rangle_f|0\rangle_B|g\rangle_B + d_2|g_{-1}\rangle_A|1_{-1}\rangle_A|0\rangle_f|0\rangle_B|g\rangle_B \\ &+ d_3|g_{-1}\rangle_A|0\rangle_A|1_{-1}\rangle_f|0\rangle_B|g\rangle_B + d_4|g_{-1}\rangle_A|0\rangle_A|0\rangle_f|1_{-1}\rangle_B|g\rangle_B \\ &+ d_5|g_{-1}\rangle_A|0\rangle_A|0\rangle_f|0\rangle_B|e_{-1}\rangle_B + d_6|g_{+1}\rangle_A|1_{+1}\rangle_A|0\rangle_f|0\rangle_B|g\rangle_B \\ &+ d_7|g_{+1}\rangle_A|0\rangle_A|1_{+1}\rangle_f|0\rangle_B|g\rangle_B + d_8|g_{+1}\rangle_A|0\rangle_A|0\rangle_f|1_{+1}\rangle_B|g\rangle_B \\ &+ d_9|g_{+1}\rangle_A|0\rangle_A|0\rangle_f|0\rangle_B|e_{+1}\rangle_B,\end{aligned} \tag{8}$$

where $|1_{\pm1}\rangle$ represents either a photon number state with one right(-1) or left(+1) circular polarized photon. Upon substituting (8) in (7) with the conditions $\lambda_{A,-1} = \lambda_{A,1} = \lambda$, $\lambda_{B,-1} = \lambda_{B,1} = \sqrt{2}\lambda$, and $\nu_{+1} = \nu_{-1} = \nu$, one has

$$d_1 = \frac{1}{2}\Big[cos(\sqrt{2}\lambda t) + 1\Big] + \frac{\lambda^2}{2(\lambda^2+\nu^2)}\Big[cos(\sqrt{1+\frac{\nu^2}{\lambda^2}}\sqrt{2}\lambda t) - 1\Big], \tag{9}$$

$$d_2 = d_6 = -\frac{i}{2\sqrt{2}}\Big[sin(\sqrt{2}\lambda t) + \frac{\lambda}{\sqrt{\lambda^2+\nu^2}}sin(\sqrt{1+\frac{\nu^2}{\lambda^2}}\sqrt{2}\lambda t)\Big], \tag{10}$$

$$d_3 = d_7 = \frac{\lambda\nu}{2(\lambda^2+\nu^2)}\Big[cos(\sqrt{1+\frac{\nu^2}{\lambda^2}}\sqrt{2}\lambda t) - 1\Big], \tag{11}$$

$$d_4 = d_8 = \frac{i}{2\sqrt{2}}\Big[sin(\sqrt{2}\lambda t) - \frac{\lambda}{\sqrt{\lambda^2+\nu^2}}sin(\sqrt{1+\frac{\nu^2}{\lambda^2}}\sqrt{2}\lambda t)\Big], \tag{12}$$

$$d_5 = d_9 = \frac{1}{2\sqrt{2}(\lambda^2+\nu^2)}\Big[\nu^2 + \lambda^2 cos(\sqrt{1+\frac{\nu^2}{\lambda^2}}\sqrt{2}\lambda t) - (\lambda^2+\nu^2)cos(\sqrt{2}\lambda t)\Big]. \tag{13}$$

We notice that $d_1 = d_2 = d_3 = d_4 = 0$, $d_5 = d_9 = 1/\sqrt{2}$, and the system is in the state $|\psi_1\rangle = \frac{1}{\sqrt{2}}(|g_{-1}\rangle_A|e_{-1}\rangle_A + |g_{+1}\rangle_A|e_{+1}\rangle_A)|0\rangle_A|0\rangle_f|0\rangle_B$ when $\sqrt{2}\lambda t = m\pi(m = 1, 3, 5, ...)$ and

$\sqrt{1+\frac{\nu^2}{\lambda^2}} = n(n = 2, 4, 6, ...)$. In this state, the atoms are completely separated from the cavity fields and in the extremely entangled state $|\Psi_t\rangle$.

In Eqs. (9)-(13), one may also find that if $\nu \gg \lambda$ the conditions $d_1 = d_2 = d_3 = d_4 = 0$ and $d_5 = d_9 = 1/\sqrt{2}$ can also be satisfied at the time $\sqrt{2}\lambda t = m\pi(m = 1, 3, 5, ...)$. It means that the requirement $\sqrt{1+\frac{\nu^2}{\lambda^2}} = n(n = 2, 4, 6, ...)$ can be loosed in the limit $\nu \gg \lambda$. In order to make the thing more clear, let us introduce the normal modes

$$\begin{aligned} c_{0,j} &= \frac{a_{A,j} - a_{B,j}}{\sqrt{2}}, &(14)\\ c_{\pm,j} &= \frac{a_{A,j} + a_{B,j} \pm \sqrt{2} b_j}{\sqrt{2}}. &(15)\end{aligned}$$

In terms of these normal modes, the Hamiltonian (6) can be rewritten as

$$\begin{aligned} H_I = \sum_{j=\pm1} \Big[&\lambda_{A,j} \frac{e^{i\sqrt{2}\nu_j t} c_{-,j} + e^{-i\sqrt{2}\nu_j t} c_{+,j} + \sqrt{2} c_{0,j}}{2} \sigma^+_{A,j} \\ &+ \lambda_{B,j} \frac{e^{i\sqrt{2}\nu_j t} c_{-,j} + e^{-i\sqrt{2}\nu_j t} c_{+,j} - \sqrt{2} c_{0,j}}{2} \sigma^+_{B,j} \Big]. \end{aligned} \tag{16}$$

As noted in (16), the normal mode $c_{0,j}$ is resonant with the atomic transitions from both $|e\rangle$ to $|g_j\rangle$ of the atom A and $|g\rangle$ to $|e_j\rangle$ of the atom B, but the normal modes $c_{\pm,j}$ off-resonant. In the limit $\nu_j \gg \lambda_{A,j}, \lambda_{B,j}$, the off-resonant modes can be safely neglected. In this case, the Hamiltonian (16) becomes

$$H_I = \frac{1}{\sqrt{2}} \sum_{j=\pm1} \Big[\lambda_{A,j} c_{0,j} \sigma^+_{A,j} - \lambda_{B,j} c_{0,j} \sigma^+_{B,j} + \text{H.c.} \Big]. \tag{17}$$

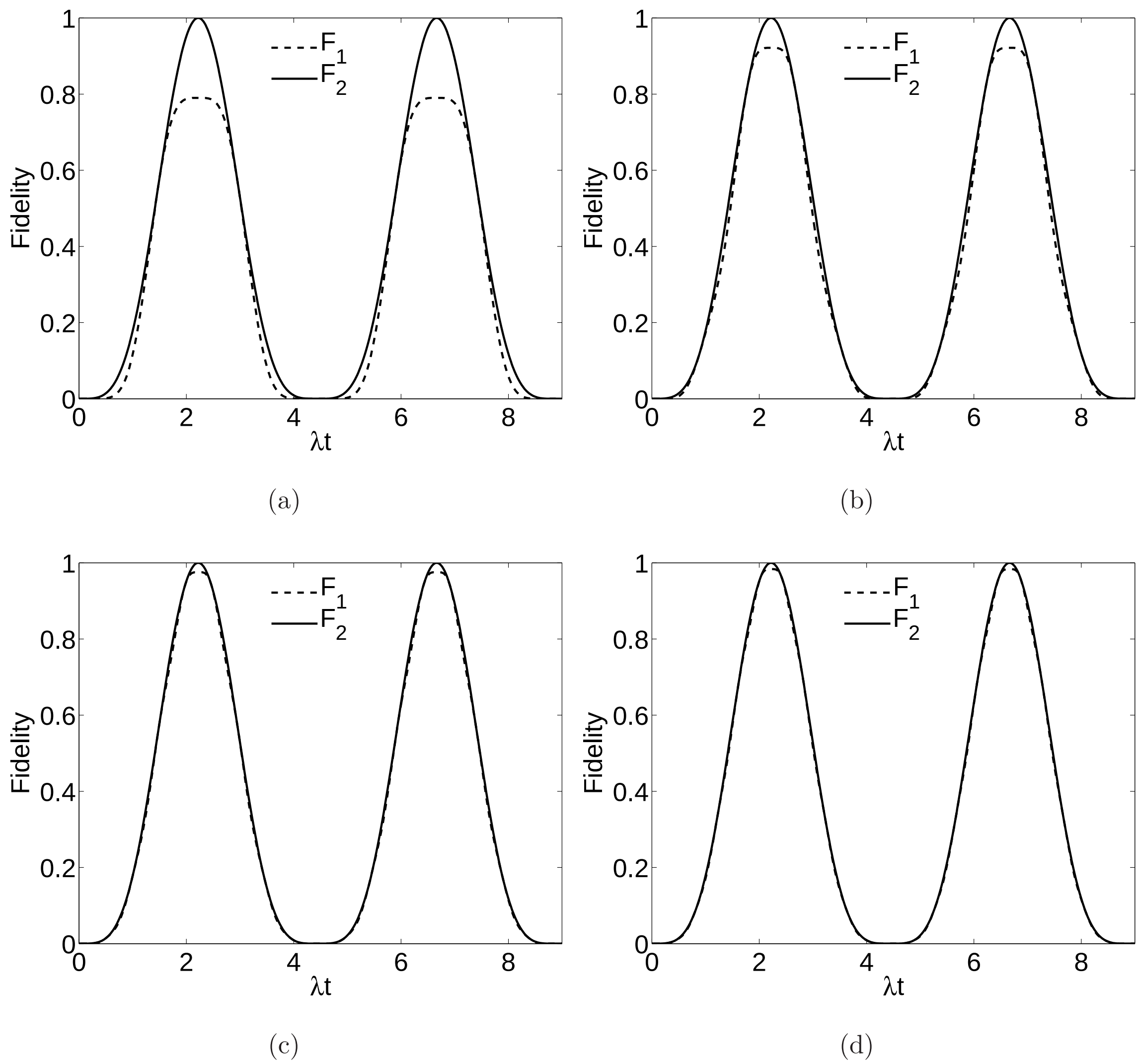
In the Hamiltonian (17), the fibre modes are completely depressed since the resonant modes c_0 do not contain the fibre modes and the original system is modeled by a system consisting of two atoms interacting with two resonant modes in one cavity. For the initial condition $|\psi_2(0)\rangle = |e\rangle_A |g\rangle_B |0\rangle_c$, where $|0\rangle_c$ is the vacuum state of the normal mode c_0, the solution of the Schrödinger equation (7) with the Hamiltonian (17) can be found to be

$$\begin{aligned} |\psi_2(t)\rangle = &\tilde{d}_1 |e\rangle_A |0\rangle_c |g\rangle_B + \tilde{d}_2 |g_{-1}\rangle_A |1_{-1}\rangle_c |g\rangle_B + \tilde{d}_3 |g_{+1}\rangle_A |1_{+1}\rangle_c |g\rangle_B \\ &+ \tilde{d}_4 |g_{-1}\rangle_A |0\rangle_c |e_{-1}\rangle_B + \tilde{d}_5 |g_{+1}\rangle_A |0\rangle_c |e_{+1}\rangle_B, \end{aligned} \tag{18}$$

where $|1_{\pm1}\rangle_c$ is a state in which there is either one right(-1) or left(+1) circular polarized photon in the normal mode c_0. Under the condition $\lambda_{A,-1} = \lambda_{A,+1} = \lambda$, and $\lambda_{B,-1} = \lambda_{B,+1} = \sqrt{2}\lambda$, the expansion coefficients in (18) are given by

$$\tilde{d}_1 = \frac{1 + cos(\sqrt{2}\lambda t)}{2}, \tilde{d}_2 = \tilde{d}_3 = \frac{-isin(\sqrt{2}\lambda t)}{2}, \tilde{d}_4 = \tilde{d}_5 = \frac{1 - cos(\sqrt{2}\lambda t)}{2\sqrt{2}}. \tag{19}$$

From Eqs.(18) and (19), one can see that at the moments $t = m\pi/\sqrt{2}\lambda (m = 1, 3, 5, ...)$ the system is in the state $|\Psi_t\rangle|0\rangle_c$ in which the two atoms are separated from the normal modes and the extremely entangled state of the atoms $|\Psi_t\rangle$ is achieved. This result depends on the condition $\nu \gg \lambda$. In order to check the approximation validity, in Fig.2, we show the fidelities $F_1 = |\langle 0_A, 0_F, 0_B|\langle\Psi_t|\psi_1(t)\rangle|^2$, where $|0_A, 0_F, 0_B\rangle$ is the vacuum state for photons in both the cavities and the fibre, and $F_2 = |_c\langle 0|\langle\Psi_t|\psi_2(t)\rangle|^2$ that corresponds to the limit $\nu \to \infty$. As shown in Fig.2, the results related to the Hamiltonians (6) and (17) become



(a) (b) (c) (d)

FIG. 2: (a)$\nu = \sqrt{8}\lambda$;(b)$\nu = \sqrt{24}\lambda$; (c)$\nu = \sqrt{80}\lambda$;(d)$\nu = \sqrt{120}\lambda$

nearly same and the approximation condition $\nu \gg \lambda$ holds very well when $\nu \geqq 10\lambda$.

From the results above, we come to the conclusion that to generate the extremely entangled state of the atoms it is needed to choose the right interaction time and the right ratio of ν to λ when ν is comparable to λ, but it is needed only to control the interaction time when $\nu \gg \lambda$.

IV. EFFECTS OF SPONTANEOUS EMISSION AND PHOTON LOSS

In this section, we investigate the influence of spontaneous emission and photon leakage on the generation of atomic entangled states. The master equation for the density matrix of the whole system is

$$\begin{aligned}\dot{\rho} = -i[H_I, \rho] &- \sum_{j=-1,1} \frac{\gamma_{A,j}}{2}(a^+_{A,j}a_{A,j}\rho - 2a_{A,j}\rho a^+_{A,j} + \rho a^+_{A,j}a_{A,j}) \\ &- \sum_{j=-1,1} \frac{\gamma_{B,j}}{2}(a^+_{B,j}a_{B,j}\rho - 2a_{B,j}\rho a^+_{B,j} + \rho a^+_{B,j}a_{B,j}) \\ &- \sum_{j=-1,1} \frac{\gamma_{f,j}}{2}(b^+_j b_j\rho - 2b_j\rho b^+_j + \rho b^+_j b_j) \\ &- \sum_{j=-1,1} \frac{\kappa_{A,j}}{2}(\sigma^+_{A,j}\sigma_{A,j}\rho - 2\sigma_{A,j}\rho\sigma^+_{A,j} + \rho\sigma^+_{A,j}\sigma_{A,j}) \\ &- \sum_{j=-1,1} \frac{\kappa_{B,j}}{2}(\sigma^+_{B,j}\sigma_{B,j}\rho - 2\sigma_{B,j}\rho\sigma^+_{B,j} + \rho\sigma^+_{B,j}\sigma_{B,j}),\end{aligned} \tag{20}$$

where H_I is given by (6), and $\gamma_{A,j}, \gamma_{B,j}$ and $\gamma_{f,j}$ are the decay rates for photons in mode j of cavities A and B, and fibre, respectively, and $\kappa_{A,j}$ and $\kappa_{B,j}$ are spontaneous emission rates that are related to the decay channel of atom A: $|e\rangle \rightarrow |g_j\rangle$ and the decay channel of atom B: $|e_j\rangle \rightarrow |g\rangle$, respectively. In solving the master equation, we always choose $\lambda_{B,\pm1} = \sqrt{2}\lambda_{A,\pm1} = \sqrt{2}\lambda$, and $\kappa_{A,\pm1} = \kappa_{B,\pm1} = \kappa_a$, $\gamma_{f,\pm1} = \gamma_f$, and $\gamma_{A,\pm1} = \gamma_{B,\pm1} = \gamma_c$. By use of the solution of Eq. (20), the fidelity $F_3 = \langle 0_A, 0_F, 0_B|\langle\Psi_t|\rho(t)|\Psi_t\rangle|0_A, 0_F, 0_B\rangle$ can be calculated. In Fig.3, the fidelity F_3 is plotted for the cases with $\kappa_a = \gamma_c = 0$ but different values of ν and γ_f.

As shown in Fig. 3(c) and (d), even for the case with $\gamma_f = \lambda$, the effect of photon leakage out of the fibre can be greatly depressed when the cavity-fiber coupling strength ν is much larger than the cavity-atom coupling strength λ. This result can be easily understood. From the discussion in the preceding section, there is only the resonant normal mode c_0 plays role when $\nu \gg \lambda$. According to (14), the resonant normal mode is not involved with the fibre mode. In the limit, therefore, the fibre mode is not excited and is always kept in the vacuum state. On the other hand, the condition $\nu \gg \lambda$ means that the transmission time of photons

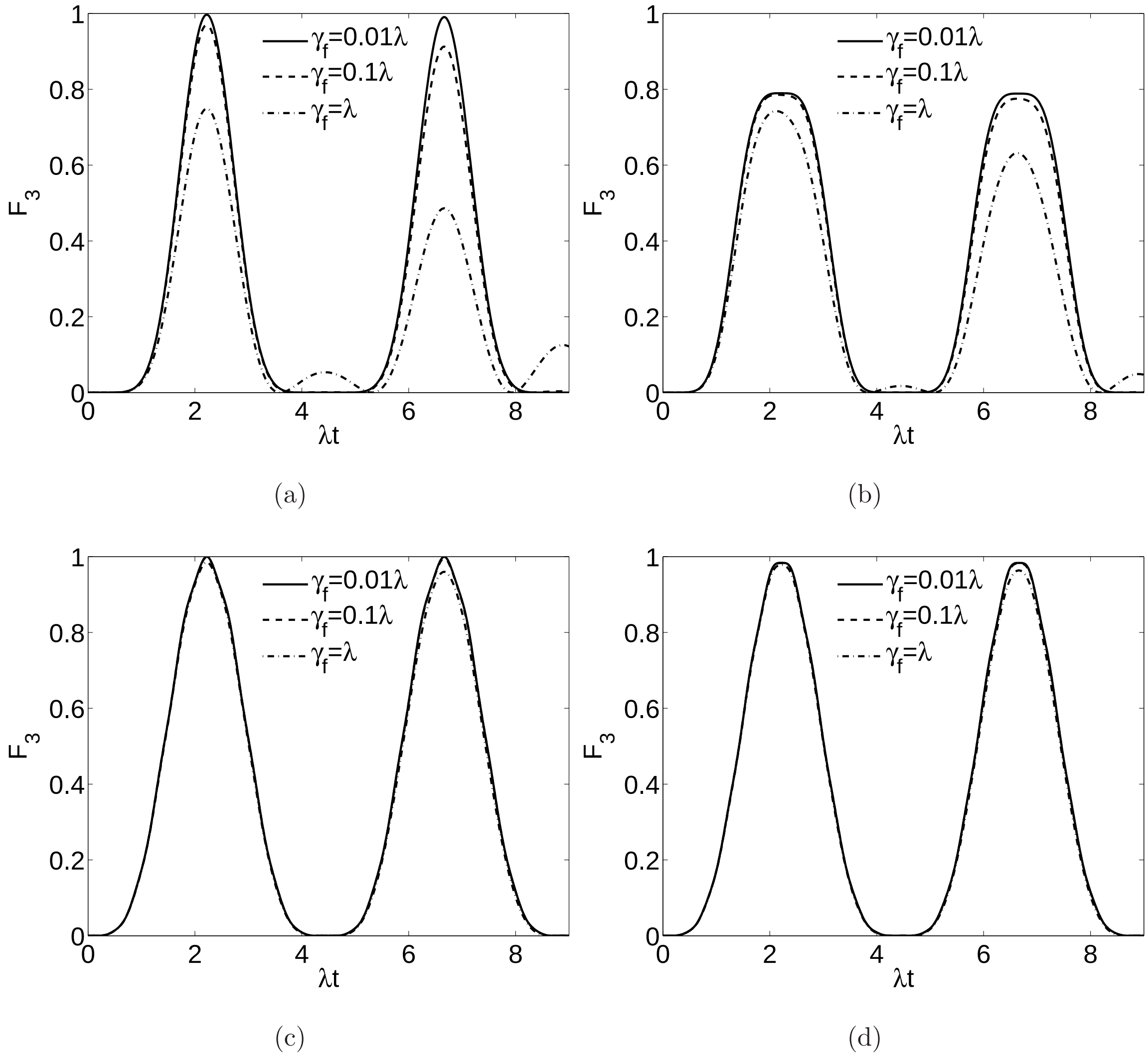


FIG. 3: (a)$\nu = \sqrt{3}\lambda$;(b)$\nu = 2\sqrt{2}\lambda$;(c)$\nu = \sqrt{99}\lambda$;(d)$\nu = \sqrt{120}\lambda$

through the fibre becomes much shorter than the interaction time of the atoms with the cavity fields and then the fibre photon is equivalently kept in the vacuum state in the whole process. This reason clearly explains why the influence of photon loss can be diminished in the limit $\nu \gg \lambda$.

From Eqs. (9)-(13), $d_3 = d_7 = 0$ at $t = m\pi/\sqrt{2}\lambda (m = 1, 3, 5, ...)$ if the condition $\sqrt{1 + \frac{\nu^2}{\lambda^2}} = n(n = 2, 4, 6, ...)$ is satisfied. It means that all the terms associated with the basic vectors with one fibre photon in (8) disappear under this condition. In this case, therefore, the fibre field in the state vector (8) is in the vacuum state. Therefore, the appropriate choice of the ratio ν/λ may be useful to get a higher fidelity of the entangled state even if the condition $\nu \gg \lambda$ is not well satisfied. In Fig. 3(a) and (b), the results with

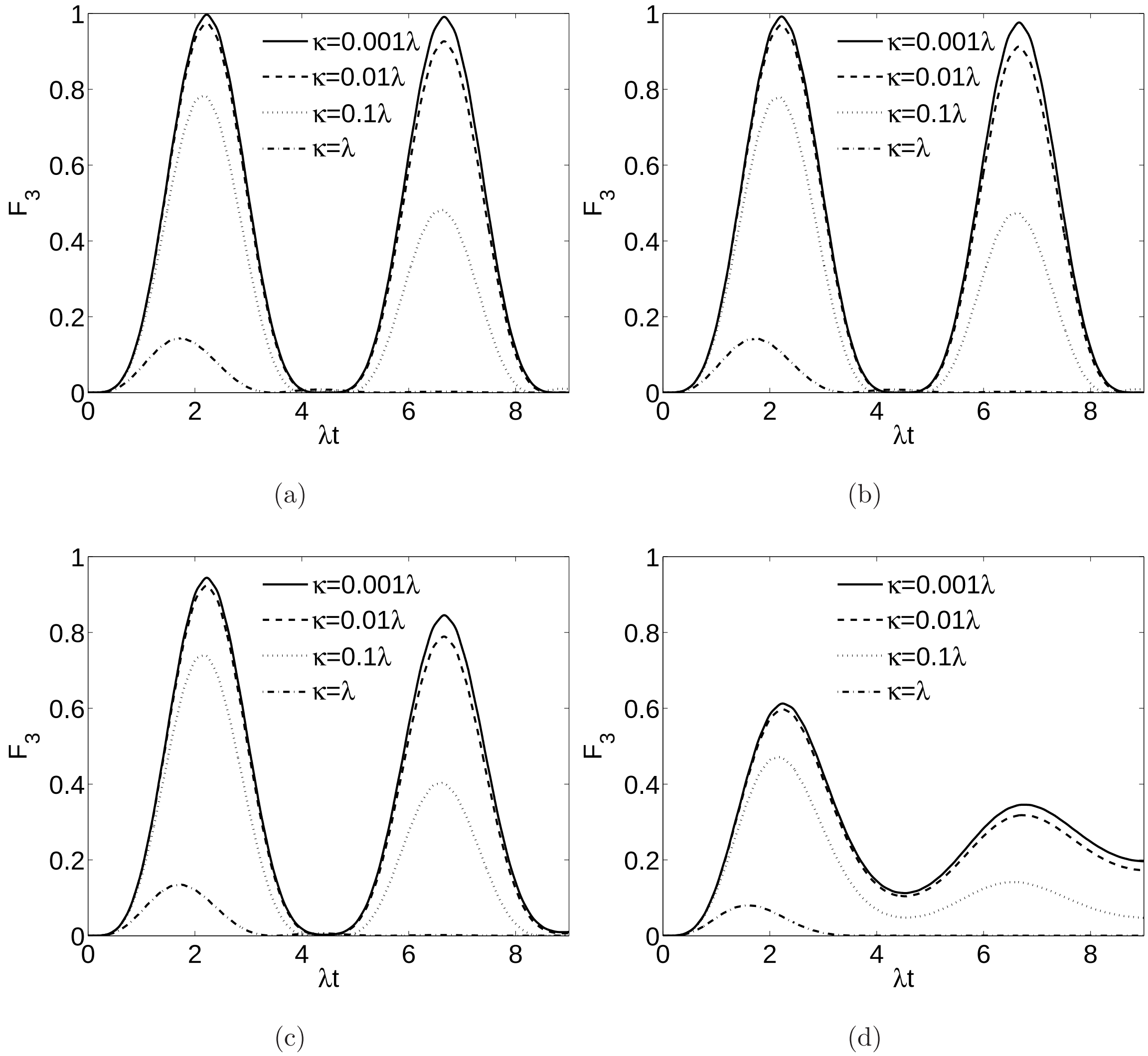


FIG. 4: (a)$\gamma = 0.001\lambda$(b)$\gamma = 0.01\lambda$;(c)$\gamma = 0.1\lambda$;(d)$\gamma = \lambda$

$\sqrt{1+\frac{\nu^2}{\lambda^2}} = 2$ and $\sqrt{1+\frac{\nu^2}{\lambda^2}} = 3$ are shown. It is observed that the former result is obviously better than the latter one when $\gamma_f < 0.1\lambda$.

Next, we investigate the influence of spontaneous emission and cavity leakage. In Figs.4, the fidelity F_3 is shown for the cases with $\nu = \sqrt{399}\lambda$ and $\gamma_f = 0$, and different values of γ_c and κ_a. Comparing these figures, we find that the atomic spontaneous emission has a stronger influence on the fidelity than the cavity photon leakage does. To obtain the fidelity higher than 0.97, one should keep the decay rates $\kappa_a \leq 0.01\lambda$ and $\gamma_c \leq 0.1\lambda$. In recent experiments [18, 19], for an optical cavity with the wavelength region $630nm \sim 850nm$, the condition ($\lambda/2\pi = 750MHz, \kappa_a/2\pi = 2.62MHz, \gamma_c/2\pi = 3.5MHz$) is achievable. Therefore, the present scheme with a high fidelity larger than 0.98 is feasible in current experiments.

V. CONCLUSIONS

In this paper, we propose a scheme to generate an entangled state of two atoms trapped in spatially separated two cavities that are connected by an optical fibre. We show that an extremely entangled state of the atoms can be deterministically generated if the ratio of the coupling constant of the cavity field with the atoms to the coupling constant of the cavity field with the fibre mode satisfies a certain condition. The scheme has three features. First, it is based on both the photon emission of a Λ-type atom and the photon absorption of a V-type atom. Therefore, in contrast to the previous schemes [10, 11, 12], either a pair of entangled photons or the photon interference process is not required. Second, since the present scheme is based on the interaction dynamics of atoms with cavity fields and then the co-instantaneous single photon detection is not required, the generation of entangled states is deterministic. Third, in contrast to the previous schemes in which manipulations such as excitation, photon emission or absorption have to be performed simultaneously on all of atoms under consideration, such manipulations are performed respectively on each of atoms in the present scheme. This may reduce difficulties resulting from manipulations performed at the same time on two atoms. The influence of various decoherence processes such as spontaneous emission and photon loss on the generation of entangled states is also investigated. We find that the effect of photon leakage out of the fibre can be greatly depressed and even ignored if the coupling of the fibre mode with the cavity fields is much stronger than the coupling of the atoms with the cavity fields. If the condition is not well satisfied, the appropriate ratio of the coupling constant of the cavity field with the atoms to the coupling constant of the cavity field with the fibre mode can also ensure a high fidelity of generating entangled states. As regards the effect of photon loss out of the cavities and spontaneous emission of the atoms, we find that the implementation of the present scheme is within the scope of the current techniques.

Acknowledgments

The authors thank Zhang-qi Yin and Yang Yang for many useful discussions. This work was supported by the Natural Science Foundation of China (Grant Nos. 10674106, 10574103,

05-06-01).

---

[1] C.H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, and W. K. Wooters, Phys. Rev. Lett. **70** 1895 (1993).

[2] A. Barenco, D. Deutsch, A. Ekert, and R. Jozsa, Phys. Rev. Lett. **74** 4083 (1995).

[3] C.H. Bennett, D.P. DiVincenzo, Nature(London) **404**, 247 (2000).

[4] M.A. Nielsen and I.L. Chuang, Quantum Computation and Quantum Information (Cambridge University Press, Cambridge, England, 2000).

[5] J.H. Reina, L. Quiroga, and N.F. Johnson, Phys. Rev. A **62**, 012305 (2000).

[6] T. Pellizzari, S.A. Gardiner, J.I. Cirac, and P. Zoller, Phys. Rev. Lett. **75** 3788 (1995).

[7] I.L. Chuang and Y. Yamamoto, Phys. Rev. A **52**, 3489 (1995).

[8] J.I. Cirac and P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995).

[9] Q.A. turchette, C.S. Wood, B.E. King,C.J.Myatt, D. Leifried, W.M. Itano, C. Monroe, and D.J. Wineland, Phys. Rev. Lett. **81**, 3631 (1998).

[10] S.Lloyd, M.S. Shahriar, J.H. Shapiro, and P.R. Hemmer, Phys. Rev. Lett. **87** 167903 (2001).

[11] X.L. Feng, Z.M. Zhang, X.D. Li, S.Q. Gong, and Z.Z. Xu, Phys. Rev. Lett. **90**, 217902 (2003).

[12] L.M. Duan, H.J. Kimber, Phys. Rev. Lett. **90**, 253601 (2003).

[13] D.E. Browne, M.B. Plenio, and S.F. Huelga, Phys. Rev. Lett. **91**, 067901 (2003).

[14] L.M. Duan, M.J. Madsen, D.L. Moehring, P. Maunz, R.N. Kohn,Jr. and C. Monroe, Phys. Rev. A **73**, 062324(2006).

[15] T. Pellizzari, Phys. Rev. Lett. **79**, 5242 (1997).

[16] A. Serafini, S. Mancini, and S. Bose, Phys. Rev. Lett. **96**, 010503 (2006).

[17] Zhang-qi Yin and Fu-li Li, quant-ph/0606152 [Phys. Rev. A (to be published)].

[18] S. M. Spillane, T. J. Kippenberg, K. J. Bahala, K. W. Goh, E. Wilcut, and H. J. Kimble, Phys. Rev. A **71** 013817 (2005) and references therein.

[19] J. R. Buck and H. J. Kimble, Phys. Rev. A**67**, 033806(2003).